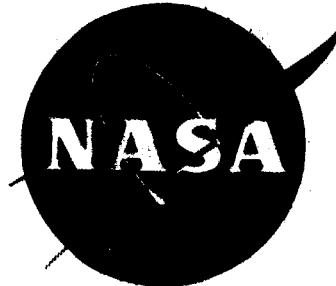


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NEUTRON CROSS SECTIONS FOR U²³⁸

by

G. D. Joanou
C. A. Stevens

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract SNPC-27

* * * *

GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE

P.O. BOX 608, SAN DIEGO 12, CALIFORNIA

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GA-6087 Rev.

TOPICAL REPORT

NEUTRON CROSS SECTIONS FOR U²³⁸

by

G. D. Joanou
C. A. Stevens

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

April 16, 1965

Contract SNPC-27

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Nuclear Reactor Division
D. Bogart

GENERAL ATOMIC

DIVISION OF

GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE
P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

NOTICE

This document has been revised to incorporate corrections to Tables 2 and 8. Table 2 was changed to provide a continuous ascension of the energy levels (6.68 to 3904.4 eV) and Table 6 column headings were corrected.

The revised pages carry the notation (Rev. 4/16/65).

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I. INTRODUCTION

A revised set of neutron cross sections has been prepared for U-238.

The compiled and evaluated data have been incorporated into the GAM-II⁽¹⁾ slowing down program and into the GATHER-II⁽²⁾ thermalization program. The literature survey associated with this report is believed to be complete to November, 1964.

II. DISCUSSION

2.1 POSSIBLE NEUTRON REACTIONS WITH U-238

The possible neutron reactions with U-238 in the energy range 0.001 eV to 15.0 MeV are listed in Table 1.⁽³⁾

Table 1
POSSIBLE NEUTRON REACTIONS WITH U-238
IN THE ENERGY RANGE 0.001 eV TO 15.0 MeV

<u>Reaction</u>	<u>Threshold, MeV</u>
n, 2n	6.07
n, 3n	11.51
n, γ	-
n, p	3.16
n, d	5.41
n, t	5.30
n, He^3	6.15
n, α	-

2.2 RESONANCE PARAMETERS

A set of resonance parameters, recently obtained by high resolution transmission measurements,⁽⁴⁾ were used in this compilation. The experimentalists report 227 resolved resonances, ranging from 6.68 eV to 3904.4 eV. Of these, 39 are believed to be either p-wave resonances or due to statistical fluctuations in the experimental data. The total contribution of these 39 resonances to the infinitely dilute resonance integral, when treated simply as s-wave resonances, is less than 0.2 barn. For this reason, only the remaining 188 resonances were used in the analysis. The resonance parameters are shown in Table 2. The presence of the additional negative energy resonance will be discussed later. The infinitely dilute resonance integral for the resolved resonances is 273.2 barns. From an examination of the resolved resonance parameters, a value of 0.9×10^{-4} was obtained for the s-wave strength function. Using this strength function, a contribution of 0.84 barn to the infinitely dilute resonance integral from unresolved s-wave resonances above 3920 eV was calculated. The use of 1.0×10^{-4} for the p-wave and d-wave strength functions was observed to give a good fit to the available capture cross section measurements from 0.01 MeV to 1.0 MeV.⁽⁵⁾ By including these higher angular momentum strength functions, the resonance integral at infinite dilution was increased by another 1.3 barns. This gives a total resonance integral at infinite dilution of 275.3 barns, which compares well with the experimental value of 280 ± 10 barns.⁽⁶⁾ In addition to the infinitely dilute resonance integral calculations, cylindrical rods of Uranium and UO₂ embedded in a moderator were analyzed and compared with experiments.⁽⁷⁾ Such comparisons have been made with considerable success before,⁽⁸⁾ and it is not surprising that the agreement is very good with the newer resonance parameters. The computations were made by Nordheim's integral method,⁽⁸⁾ and the results are shown in Tables 3 and 4.

2.3 LOW ENERGY CROSS SECTIONS

The contribution from the positive energy resonance parameters shown in Table 2 to the 2200 meters/sec capture cross section is 2.44 barns. However, the measured value of the capture cross section is 2.71 barns.⁽⁹⁾ For this reason, the bound level at -24.56 eV was postulated. If the bound level contribution is included we get a capture cross section of 2.70 barns. The capture and scattering cross sections were computed, from the resonance parameters, at the 101 energy points required for the GATHER-II computer program.⁽²⁾ The results are shown in Table 5.

Table 2
 ^{238}U RESONANCE PARAMETERS

E_o eV	Γ_n^o (mv)	E_o eV	Γ_n^o (mv)	E_o eV	Γ_n^o (mv)
-24.56	1.60	708.46	0.70	1245.12	6.50
6.68	0.59	721.80	0.05	1267.01	0.75
*10.2	0.0004	*730.10	0.03	1273.20	0.80
21.00	1.90	732.26	0.05	1298.44	0.88
36.70	5.14	*742.95	0.02	1317.21	0.11
66.30	3.09	765.05	0.24	1335.72	0.03
80.77	0.23	779.14	0.06	1393.00	3.70
*90.00	0.008	790.88	0.18	1405.11	2.05
102.78	6.50	821.58	2.05	*1410.00	0.03
116.93	3.33	*846.62	0.02	*1417.00	0.03
145.80	0.07	851.02	1.90	1419.64	0.25
165.54	0.27	856.15	2.75	1427.73	0.80
190.34	10.90	866.52	0.14	1444.10	0.57
208.65	3.90	*891.29	0.03	1473.80	2.05
237.40	1.80	905.11	1.50	1523.10	5.50
*242.88	0.01	909.90	0.03	1532.00	0.05
*263.94	0.014	925.18	0.28	*1546.00	0.02
273.74	1.52	*932.50	0.01	1550.00	0.03
291.11	0.90	936.87	4.80	1565.00	0.05
311.12	0.056	958.43	5.10	1598.16	8.00
347.92	4.40	991.78	11.00	1622.89	2.10
376.92	0.058	1000.30	0.04	1638.19	1.00
397.56	0.30	1011.25	0.06	*1645.40	0.02
410.23	0.95	1023.00	0.20	1662.08	4.00
434.19	0.40	1029.08	0.10	1688.33	1.90
*454.17	0.02	*1033.16	0.02	*1700.71	0.02
463.31	0.24	1053.93	2.30	1709.40	1.35
478.70	0.14	1068.10	0.02	1723.00	0.33
*488.89	0.02	*1070.50	0.01	1744.00	0.04
518.59	1.90	*1081.10	0.02	1755.80	1.50
535.49	1.60	*1094.80	0.02	1782.30	11.00
*556.05	0.02	1098.35	0.45	1797.70	0.05
580.20	1.12	*1102.34	0.02	1808.26	0.40
595.15	3.35	1108.88	0.90	1845.60	0.31
619.94	1.14	1131.45	0.06	1902.27	0.48
*623.53	0.017	1140.38	6.50	1917.10	0.50
628.67	0.16	1167.46	2.35	1968.66	13.00
661.18	4.50	1177.62	1.85	1974.65	10.50
*677.00	0.02	1194.96	2.65	2023.58	4.50
693.23	1.30	1210.93	0.26	2031.06	1.10

*Levels which are either p-wave or uncertain.

$\Gamma_\gamma = 25.0$ mv for all resonances.

Table 2
 ^{238}U RESONANCE PARAMETERS

E_o eV	$\Gamma_n o$ (mv)	E_o eV	$\Gamma_n o$ (mv)	E_o eV	$\Gamma_n o$ (mv)
2088.63	0.30	2750.1	0.75	3387.8	0.14
2096.49	0.22	2761.9	0.30	3409.0	1.80
2124.35	0.10	2787.9	0.20	*3419.0	0.05
2145.95	0.75	*2798.0	0.05	3436.9	3.25
2152.77	3.80	2806.2	0.13	3459.1	6.50
2172.00	0.05	2828.6	0.17	*3470.0	0.02
2185.99	7.80	*2845.2	0.05	3484.3	2.00
*2194.00	0.05	2866.1	1.48	3492.0	0.19
2201.42	2.40	2882.9	9.80	3512.0	0.05
2229.96	0.10	2897.8	0.50	3526.0	0.18
2235.73	0.10	*2908.5	0.05	3561.5	2.40
*2241.53	0.03	2923.6	0.08	3574.0	4.00
2259.06	1.38	2932.3	0.46	3593.0	0.26
2266.43	3.05	2956.3	0.28	*3600.0	0.05
2281.27	2.30	2967.4	0.15	3611.0	0.05
2288.70	0.05	*2974.0	0.05	3625.0	0.05
*2302.0	0.02	2987.4	0.10	3630.0	3.60
2315.9	0.30	3003.1	1.70	*3647.0	0.05
2337.4	0.10	3015.0	0.13	*3674.0	0.05
2352.0	1.30	3029.0	2.50	3693.0	4.00
2356.0	1.30	3041.0	0.05	3717.7	1.00
2392.5	0.23	3060.2	0.50	3733.3	2.50
2410.2	0.09	3081.1	0.08	3764.7	0.56
2426.5	1.65	3109.4	1.80	3783.7	4.50
2446.2	2.25	3133.2	0.10	*3799.7	0.05
2454.0	0.05	3149.0	1.10	3832.0	0.10
2489.8	1.10	3169.0	0.18	3858.1	5.50
2520.7	1.20	3179.4	1.10	3871.3	4.00
2548.7	6.80	3189.0	0.77	3895.0	0.08
2559.3	4.30	3206.0	1.00	3904.4	3.60
2580.7	4.80	3226.0	0.40		
2598.7	11.00	3249.2	0.20		
*2604.0	0.05	3280.0	1.80		
2620.6	0.80	3295.0	0.15		
2631.6	0.02	3310.9	1.65		
2672.8	3.40	3321.3	1.42		
2695.6	0.45	3334.0	1.00		
2716.8	1.36	3355.7	1.30		
*2730.0	0.05	3371.0	0.05		

*Levels which are either p-wave or uncertain.

$\Gamma_\gamma = 25.0$ mv for all resonances.

Table 3

**COMPARISON OF CALCULATED VALUES AND VALUES FROM
HELLSTRAND'S EMPIRICAL FORMULAS FOR THE
RESONANCE INTEGRALS OF URANIUM METAL**

<u>Uranium Metal (Density of 18.7)</u>						
Radius (cm)	0.1055	0.211	0.422	0.844	1.69	0.0
S/M	1.015	0.507	0.254	0.127	0.0634	
Resolved Resonance Contribution	26.70	19.11	13.76	10.02	7.36	273.2
Unresolved S-wave Contribution	0.76	0.70	0.64	0.58	0.53	0.84
Higher λ Contribution (self-shielding neglected)	1.31	1.31	1.31	1.31	1.31	1.31
Predicted Total Resonance Integral	28.77	21.12	15.71	11.91	9.20	275.3
$2.95 + 25.8\sqrt{\frac{S}{M}}$ Experiment	28.93	21.29	15.98	12.16	9.45	280±10*

* Not computed from the empirical formula.

Table 4
 COMPARISON OF CALCULATED VALUES AND VALUES FROM
 HELLSTRAND'S EMPIRICAL FORMULAS FOR THE
 RESONANCE INTEGRALS OF UO_2

	UO_2 (Density 10.2)					
Radius (cm)	0.125	0.25	0.50	1.0	2.0	0.0
S/M	1.570	0.785	0.393	0.196	0.098	
Resolved Resonance Contribution	35.76	25.82	19.03	14.46	11.48	273.2
Unresolved s-wave Contribution	0.80	0.76	0.71	0.66	0.61	0.84
Higher ℓ Contribution (self-shielding neglected)	1.31	1.31	1.31	1.31	1.31	1.31
Predicted Total Resonance Integral	37.87	27.89	21.09	16.43	13.40	275.3
$4.15 + 26.6 \frac{S}{M}$ (Experiment)	37.45	27.72	20.85	15.93	12.50	$280 \pm 10^*$

* Not computed from the empirical formula.

Table 5
LOW ENERGY CROSS SECTIONS FOR U²³⁸

Point	E(eV)	σ_Y (barns)	σ_s (barns)	σ_t (barns)	Point	E(eV)	σ_Y (barns)	σ_s (barns)	σ_t (barns)
1	0.001	13.51	10.74	24.24	31	0.250	0.892	10.73	11.62
2	0.002	9.55	10.73	20.29	32	0.260	0.876		11.61
3	0.004	6.76	10.73	17.49	33	0.270	0.862		11.60
4	0.005	6.04	10.73	16.78	34	0.280	0.848		11.58
5	0.007	5.11	10.73	15.84	35	0.290	0.835		11.57
6	0.008	4.78		15.51	36	0.300	0.822		11.56
7	0.010	4.28		15.01	37	0.310	0.810		11.54
8	0.015	3.50		14.23	38	0.320	0.799		11.53
9	0.020	3.03		13.76	39	0.330	0.788		11.52
10	0.025	2.70		13.43	40	0.340	0.778		11.51
11	0.030	2.48		13.21	41	0.350	0.768		11.50
12	0.040	2.15		12.88	42	0.360	0.759		11.49
13	0.050	1.93		12.66	43	0.380	0.741		11.48
14	0.060	1.76		12.49	44	0.414	0.715		11.45
15	0.065	1.69		12.43	45	0.420	0.710		11.44
16	0.070	1.63		12.37	46	0.430	0.703		11.44
17	0.075	1.58		12.31	47	0.450	0.690		11.42
18	0.080	1.53		12.26	48	0.460	0.684		11.42
19	0.085	1.49		12.22	49	0.470	0.678		11.41
20	0.090	1.45		12.18	50	0.475	0.675		11.41
21	0.095	1.41		12.14	51	0.480	0.672		11.41
22	0.100	1.37		12.11	52	0.490	0.667		11.40
23	0.120	1.26		11.99	53	0.500	0.661		11.40
24	0.140	1.17		11.90	54	0.532	0.645		11.38
25	0.160	1.10		11.83	55	0.550	0.636		11.37
26	0.180	1.04		11.77	56	0.575	0.626		11.36
27	0.200	0.989		11.72	57	0.590	0.619		11.35
28	0.220	0.946		11.68	58	0.600	0.615		11.35
29	0.230	0.727		11.66	59	0.625	0.606		11.34
30	0.240	0.909		11.64	60	0.650	0.597		11.33

Table 5 (Cont.)

LOW ENERGY CROSS SECTIONS FOR U²³⁸

Point	E(eV)	σ_Y (barns)	σ_s (barns)	σ_t (barns)	Point	E(eV)	σ_Y (barns)	σ_s (barns)	σ_t (barns)
61	0.683	0.586	10.73	11.32	91	1.600	0.474	10.73	11.21
62	0.700	0.581		11.32	92	1.700	0.472		11.21
63	0.750	0.567		11.30	93	1.780	0.472		11.21
64	0.800	0.555		11.29	94	1.860	0.472		11.21
65	0.850	0.544		11.28	95	1.900	0.472		11.21
66	0.876	0.539		11.27	96	2.000	0.474		11.22
67	0.890	0.536		11.27	97	2.100	0.477		11.22
68	0.910	0.533		11.27	98	2.200	0.481		11.22
69	0.930	0.529		11.27	99	2.290	0.485		11.23
70	0.950	0.526		11.26	100	2.330	0.487		11.23
71	0.970	0.523		11.26	101	2.380	0.490		11.23
72	0.980	0.522		11.26					
73	0.990	0.520		11.26					
74	1.000	0.518		11.25					
75	1.025	0.515		11.25					
76	1.050	0.512		11.25					
77	1.060	0.510		11.25					
78	1.070	0.509		11.25					
79	1.080	0.508		11.24					
80	1.090	0.507		11.24					
81	1.110	0.504		11.24					
82	1.125	0.503		11.24					
83	1.130	0.502		11.24					
84	1.150	0.500		11.24					
85	1.200	0.495		11.23					
86	1.250	0.491		11.23					
87	1.300	0.487		11.22					
88	1.350	0.484		11.22					
89	1.440	0.479		11.22					
90	1.500	0.477		11.22					

2.4 CROSS SECTIONS IN THE ENERGY RANGE 0.01 MeV TO 15.0 MeV

2.4.1 Total Cross Section

An excellent compilation of neutron cross sections for U-238 in the energy range 1 keV to 15.0 MeV has recently been published by K. Parker.⁽⁵⁾ Parker's compilation includes most of the post BNL-325⁽⁹⁾ data. The total cross sections tabulated in Table 6 have been abstracted from Parker's compilation.

2.4.2 Inelastic Scattering

Optical model calculations, together with Hauser-Feshbach calculations,⁽¹⁰⁾ were used to compute total inelastic cross sections and elastic cross sections in the energy range in which the level scheme is known. The potential chosen for the optical model calculations had a real part of the Woods-Saxon⁽¹¹⁾ form and an imaginary part of the Gaussian form.⁽¹²⁾ The parameters chosen for the potential were the "set A" which was used by Moore and Auerbach in their calculations for U-238.⁽¹³⁾ The energy level scheme for U-238 was taken to be the one recommended by Moore and Auerbach: 0.0(0+), 0.045(2+), 0.148(4+), 0.308(6+), 0.654(1-), 0.710(3-), 0.728(5-), 0.935(0+), 0.986(2+), 1.03(2+), 1.11(3+), 1.13(4+), 1.17(4+). Undoubtedly, a number of levels have been missed in the upper energy range of the level scheme. The presence of other levels will decrease the inelastic cross section of those levels which are analyzed here. However, only those levels mentioned above were considered in the analysis. The capture and fission cross sections in the energy range from 0.05 MeV to 1.15 MeV are not negligible. Accordingly, the inelastic cross sections which are computed in the Hauser-Feshbach calculation by neglecting all reactions other than scattering, have been renormalized to take capture and fission into account. This is done by multiplying the compound elastic cross section and the cross section for exciting each excited level by the factor r , where

$$r = 1 - \frac{\sigma_{n,\gamma} + \sigma_{n,f}}{\sigma_r}, \quad (1)$$

$\sigma_{n,\gamma}$ = capture cross section

$\sigma_{n,f}$ = fission cross section

σ_r = cross section for formation of compound nucleus.

Neither the shape elastic cross section nor the total cross section are affected by the renormalization. The reaction cross section, to which

Table 6
NEUTRON CROSS SECTIONS OF U²³⁸
FROM 0.01 MeV TO 15.0 MeV

E MeV	σ_T barns	σ_{non} barns	σ_{el} barns	$\sigma_{n,\gamma}$ barns	σ_f barns	$\sigma_{n, 2n}$ barns	$\sigma_{n, 3n}$ barns	σ_{in} barns	$\bar{\nu}$
15.0	5.70	2.90	2.80	0.003	1.27	0.58	0.88	0.167	4.623
14.5	5.80	2.91	2.89	0.003	1.22	0.70	0.82	0.167	4.546
14.0	5.70	2.92	2.78	0.003	1.13	0.85	0.77	0.167	4.469
13.5	5.42	2.93	2.49	0.003	1.07	1.00	0.67	0.187	4.392
13.0	5.70	2.94	2.76	0.003	1.03	1.22	0.46	0.227	4.315
12.5	5.75	2.96	2.79	0.003	1.01	1.35	0.31	0.287	4.238
12.0	5.80	2.97	2.83	0.003	1.02	1.42	0.14	0.387	4.161
11.5	5.82	2.98	2.84	0.004	1.01	1.49	0.00	0.476	4.084
11.0	5.85	3.00	2.85	0.004	1.00	1.51		0.486	4.007
10.5	5.93	3.01	2.92	0.004	1.00	1.50		0.506	3.930
10.0	6.00	3.02	2.98	0.004	1.02	1.49		0.506	3.853
9.5	6.05	3.03	3.02	0.005	1.03	1.46		0.535	3.776
9.0	6.10	3.04	3.06	0.005	1.040	1.39		0.605	3.699
8.75	6.18	3.05	3.13	0.005	1.040	1.35		0.655	3.661
8.5	6.22	3.06	3.16	0.005	1.040	1.28		0.735	3.622
8.25	6.31	3.07	3.24	0.005	1.030	1.21		0.825	3.583
8.0	6.35	3.09	3.26	0.006	1.020	1.12		0.944	3.545
7.75	6.40	3.10	3.30	0.006	1.000	1.04		1.054	3.507
7.50	6.58	3.11	3.47	0.006	1.000	0.95		1.154	3.468
7.25	6.71	3.12	3.59	0.006	1.000	0.78		1.334	3.430
7.00	6.80	3.13	3.67	0.006	0.960	0.51		1.654	3.391
6.75	6.90	3.14	3.76	0.007	0.810	0.23		2.093	3.352
6.50	7.00	3.15	3.85	0.007	0.800	0.08		2.263	3.314
6.25	7.01	3.16	3.85	0.007	0.710	0.03		2.413	3.276
6.00	7.18	3.17	4.01	0.008	0.590	0.00		2.572	3.237
5.75	7.40	3.18	4.22	0.008	0.580			2.592	3.198
5.50	7.50	3.19	4.31	0.008	0.572			2.610	3.160
5.25	7.60	3.20	4.40	0.009	0.571			2.620	3.121
5.00	7.70	3.20	4.50	0.009	0.570			2.621	3.083
4.75	7.71	3.20	4.51	0.010	0.560			2.630	3.041
4.50	7.80	3.21	4.59	0.011	0.560			2.639	3.006
4.25	7.85	3.22	4.63	0.012	0.560			2.648	2.967
4.00	7.84	3.23	4.61	0.013	0.560			2.657	2.929
3.75	7.87	3.24	4.63	0.0140	0.560			2.666	2.890
3.50	7.90	3.24	4.66	0.016	0.560			2.664	2.852
3.25	7.88	3.25	4.63	0.0180	0.560			2.672	2.813
3.00	7.80	3.23	4.57	0.0200	0.560			2.650	2.775
2.75	7.72	3.22	4.50	0.024	0.560			2.636	2.736

Table 6 (Cont.)

NEUTRON CROSS SECTIONS OF U²³⁸
FROM 0.01 MeV TO 15.0 MeV

E MeV	σ_T barns	σ_{non} barns	σ_{el} barns	$\sigma_{n,\gamma}$ barns	σ_f barns	$\sigma_{n, 2n}$ barns	$\sigma_{n, 3n}$ barns	σ_{in} barns	$\bar{\nu}$
2.50	7.62	3.18	4.44	0.027	0.560	0.00	0.000	2.593	2.698
2.25	7.55	3.09	4.46	0.033	0.560			2.497	2.659
2.00	7.44	2.99	4.45	0.043	0.560			2.387	2.621
1.75	7.20	2.79	4.41	0.053	0.470			2.267	2.582
1.50	6.96	2.56	4.40	0.077	0.260			2.223	2.544
1.25	6.84	2.310	4.53	0.106	0.041			2.163	2.506
1.00	6.98	2.000	4.98	0.140	0.017			1.843	2.467
1.15	6.85	2.172	4.678	0.126	0.035			2.011	2.490
1.10	6.90	2.122	4.778	0.126	0.026			1.97	2.482
1.05	6.91	2.038	4.872	0.138	0.020			1.88	2.475
0.9	7.00	1.883	5.117	0.150	0.010			1.723	2.451
0.85	7.22	1.823	5.397	0.151	0.004			1.666	2.443
0.80	7.30	1.776	5.524	0.150	0.003			1.623	2.436
0.75	7.51	1.686	5.824	0.146	0.002			1.538	2.428
0.7	7.70	1.638	6.062	0.143	0.0014			1.494	2.420
0.65	7.89	1.499	6.391	0.135	0.0013			1.363	2.413
0.6	8.10	1.497	6.603	0.132	0.001			1.364	2.405
0.55	8.31	1.446	6.864	0.129	0.000			1.317	2.398
0.50	8.56	1.406	7.154	0.125				1.281	2.390
0.45	8.80	1.357	7.443	0.124				1.233	2.382
0.40	9.15	1.298	7.852	0.124				1.174	2.374
0.35	9.50	1.200	8.300	0.125				1.075	2.367
0.30	9.86	1.122	8.738	0.135				0.987	2.359
0.25	10.3	1.046	9.254	0.155				0.891	2.351
0.20	10.7	0.953	9.747	0.181				0.772	2.344
0.15	11.2	0.850	10.35	0.220				0.630	2.336
0.10	12.0	0.671	11.329	0.265				0.406	2.328
0.09	12.1	0.613	11.487	0.275				0.338	2.327
0.08	12.3	0.547	11.753	0.292				0.255	2.325
0.07	12.5	0.472	12.028	0.310				0.162	2.324
0.06	12.7	0.425	12.275	0.330				0.095	2.322
0.05	12.9	0.386	12.514	0.358				0.028	2.321
0.04	13.2	0.389	12.811	0.389				0.000	2.319
0.03	13.6	0.430	13.17	0.430					2.318
0.02	14.6	0.492	14.108	0.492					2.316
0.01	15.0	0.660	14.340	0.660					2.315

capture and fission are added after the renormalization, also has the value predicted by the optical model. The partial inelastic cross sections are given in Table 7.

Above 1.15 MeV the inelastic cross section was obtained from the non-elastic cross section in the following manner:

$$\sigma_{in} = \sigma_{non} - \sigma_{n,\gamma} - \sigma_{n,f} - \sigma_{n,2n} - \sigma_{n,3n}$$

The resulting data are shown in Tables 6 and 7.

2.4.3 Non-Elastic Cross Section

A considerable number of direct measurements of the non-elastic scattering cross section of U-238 exist. These measurements have been summarized by K. Parker.⁽⁵⁾ Below 1.15 MeV the non-elastic cross section was obtained in the following manner:

$$\sigma_{non} = \sigma_{in} + \sigma_{n,f} + \sigma_{n,\gamma}$$

Above 1.15 MeV the available direct measurements were plotted versus energy and a smooth curve was drawn through these data joining the calculated non-elastic cross section at 1.15 MeV. The resulting evaluated cross sections are shown in Table 6.

2.4.4 Elastic Cross Section

The elastic scattering cross section was obtained by subtracting the non-elastic cross section from the total cross section. The resulting data are shown in Table 6.

These data are not in particularly good agreement with Smith's⁽¹⁴⁾ measurements of the elastic scattering cross sections. However, the recommended data are in reasonably good agreement with measurements of the total scattering cross section (elastic plus inelastic).⁽¹⁵⁾

2.4.5 Legendre Expansion Coefficients

Legendre coefficients for the angular distribution of elastically scattered neutrons in the center of mass system were obtained from a least squares analysis of the data in BNL-400⁽¹⁶⁾ and Howerton's⁽¹⁷⁾ compilation.

7

PARTIAL INELASTIC CROSS SECTIONS FOR U₂₃₈

E(MeV)		Energy of Excited States (MeV)					
		0.148	0.308	0.654	0.710	0.728	0.935
		0.045	0.113	0.205	0.275	0.366	0.455
1.15	0.738	0.345	0.317	0.323	0.229	0.366	0.748
1.10	0.781	0.343	0.027	0.333	0.221	0.031	0.0685
1.05	0.831	0.330	0.020	0.340	0.205	0.024	0.0567
1.00	0.876	0.324	0.018	0.346	0.189	0.017	0.045
0.90	0.950	0.290	0.011	0.327	0.139	0.006	0.0
0.85	0.982	0.270	0.0083	0.297	0.108	0.001	
0.80	1.019	0.251	0.0056	0.268	0.0771	0.0003	
0.75	1.070	0.235	0.0038	0.210	0.020	0.0	
0.70	1.12	0.220	0.002	0.152	0.0		
0.65	1.170	0.193	0.0				
0.60	1.198	0.166					
0.55	1.180	0.137					
0.50	1.172	0.109					
0.45	1.150	0.083					
0.40	1.117	0.0572					
0.35	1.042	0.0333					
0.30	0.978	0.0094					
0.25	0.890	0.001					
0.20	0.772	0.0					
0.15	0.630						
0.10	0.4056						
0.09	0.205						
0.08	0.177						
0.07	0.125						
0.06	0.075						
0.05	0.028						
0.04	0.00						
0.03	0.00						

These data, old and new, were analyzed in the following manner:

$$\sigma_s(E, \mu) = \frac{\sigma_s(E)}{4\pi} \sum_{\ell} (2\ell + 1) f_{\ell} P_{\ell}(\mu) \quad (1)$$

where $\sigma_s(E, \mu)$ is the scattering cross section per unit solid angle in the center of mass system for a neutron, at energy E scattered through an angular deflection given by $\cos^{-1}\mu$.

The Legendre coefficients, calculated by a least squares fit to the data, were plotted versus energy and smooth curves were then drawn through the data. The Legendre expansion coefficients obtained by this procedure are listed in Table 8.

2.4.6 Mean Number of Neutrons Per Fission

A considerable number of direct measurements of the number of neutrons per fission, \bar{V} , in U-238 have been carried out (cf. Refs). A recent series of measurements have been made by Asplund-Nelson⁽¹⁸⁾ et.al. in the energy range from 1.5 to 7.5 MeV and also at 14.8 MeV. The \bar{V} values are relative to $\bar{V} = 3.775$ in the spontaneous fission of Cf - 252. These data are well represented by the relationship $\bar{V}(E) = 2.313 \pm 0.154E$ from the fission threshold to 14.8 MeV. The data shown in Table 6 have been calculated using this relationship.

2.4.7 Fission Cross Section

The fission cross section of U-238 tabulated in this report was taken from the recommended values given in Reference 5 between 15.0 and 2.00 MeV. Between 2.00 MeV and the threshold some differences exist due primarily to a slightly different interpretation of the available data in this energy range. The resulting data are tabulated in Table 6.

2.4.8 Capture Cross Section

Considerable disagreement exists among the various measurements of the capture cross section of U-238. The data shown in Table 6 were obtained by smooth curves drawn through the data reported in Reference 5.

2.4.9 n, 2n Cross Section

The n, 2n cross section shown in Table 6 was taken directly from Reference 5.

Table 8
LEGENDRE EXPANSION COEFFICIENTS FOR U²³⁸

E (MeV)	f ₁	f ₂	f ₃	f ₄	f ₅	f ₆	f ₇	f ₈	f ₉	f ₁₀	f ₁₁	f ₁₂
15.0	0.488	0.788	0.348	0.599	0.258	0.409	0.196	0.238	0.142	0.078	0.100	-0.030
14.5	0.501	0.777	0.358	0.589	0.261	0.407	0.204	0.239	0.149	0.085	0.104	-0.030
14.0	0.514	0.766	0.370	0.577	0.264	0.405	0.207	0.240	0.154	0.091	0.106	-0.030
13.5	0.528	0.757	0.382	0.566	0.268	0.402	0.211	0.241	0.157	0.096	0.106	-0.030
13.0	0.541	0.749	0.394	0.556	0.271	0.399	0.214	0.240	0.159	0.099	0.105	-0.030
12.5	0.554	0.738	0.406	0.546	0.275	0.394	0.217	0.238	0.159	0.100	0.102	-0.030
12.0	0.567	0.728	0.417	0.535	0.278	0.388	0.218	0.234	0.157	0.099	0.097	-0.030
11.5	0.580	0.718	0.427	0.524	0.281	0.380	0.217	0.229	0.156	0.096	0.089	-0.030
11.0	0.592	0.707	0.436	0.513	0.286	0.369	0.215	0.221	0.151	0.091	0.081	-0.030
10.5	0.602	0.696	0.444	0.502	0.289	0.356	0.211	0.211	0.146	0.086	0.071	-0.030
10.0	0.612	0.685	0.450	0.491	0.291	0.340	0.205	0.200	0.139	0.077	0.061	-0.030
9.5	0.621	0.674	0.454	0.481	0.291	0.324	0.196	0.186	0.129	0.068	0.050	-0.030
9.0	0.629	0.664	0.455	0.470	0.290	0.306	0.187	0.171	0.118	0.059	0.040	-0.030
8.75	0.632	0.659	0.455	0.465	0.289	0.298	0.181	0.163	0.112	0.054	0.035	-0.030
8.5	0.634	0.653	0.455	0.459	0.288	0.288	0.176	0.154	0.105	0.049	0.030	-0.030
8.25	0.636	0.649	0.454	0.454	0.285	0.278	0.170	0.145	0.098	0.043	0.025	-0.030
8.0	0.637	0.644	0.453	0.448	0.284	0.268	0.163	0.136	0.090	0.038	0.020	-0.030
7.75	0.638	0.639	0.451	0.442	0.281	0.258	0.156	0.127	0.081	0.031	0.015	-0.030
7.5	0.639	0.635	0.450	0.436	0.278	0.249	0.149	0.117	0.072	0.026	0.011	-0.030
7.25	0.639	0.630	0.448	0.432	0.275	0.238	0.142	0.107	0.063	0.020	0.007	-0.030
7.0	0.640	0.625	0.446	0.425	0.272	0.228	0.134	0.097	0.053	0.014	0.004	-0.030
6.75	0.639	0.620	0.443	0.420	0.267	0.218	0.127	0.086	0.045	0.010	0.002	-0.030
6.50	0.638	0.615	0.441	0.414	0.263	0.208	0.119	0.076	0.036	0.006	0.000	-0.029
6.25	0.637	0.610	0.438	0.409	0.258	0.198	0.113	0.067	0.027	0.002		-0.028
6.00	0.635	0.603	0.435	0.401	0.252	0.187	0.105	0.057	0.019	0.000		-0.027
5.75	0.633	0.597	0.431	0.395	0.246	0.177	0.087	0.048	0.013			-0.025
5.50	0.630	0.590	0.427	0.387	0.238	0.167	0.091	0.039	0.006			-0.024
5.25	0.626	0.582	0.423	0.380	0.231	0.156	0.085	0.030	0.002			-0.021
5.00	0.623	0.574	0.417	0.373	0.223	0.146	0.078	0.022	0.000			-0.019
4.75	0.618	0.565	0.412	0.365	0.215	0.136	0.072	0.015				-0.015
4.50	0.613	0.555	0.406	0.357	0.207	0.125	0.066	0.009				-0.012
4.25	0.617	0.546	0.399	0.349	0.197	0.115	0.060	0.004				-0.006
4.00	0.601	0.536	0.390	0.340	0.190	0.105	0.053	0.000				-0.000
3.75	0.596	0.525	0.382	0.330	0.190	0.095	0.046					
3.50	0.589	0.512	0.374	0.319	0.171	0.084	0.038					
3.25	0.584	0.50	0.365	0.308	0.160	0.069	0.032					
3.00	0.577	0.485	0.356	0.295	0.150	0.063	0.024					
2.75	0.570	0.470	0.348	0.279	0.139	0.054	0.019					
2.50	0.563	0.453	0.337	0.271	0.125	0.043	0.013					
2.25	0.554	0.434	0.328	0.260	0.109	0.033	0.008					
2.00	0.536	0.408	0.319	0.241	0.091	0.023	0.004					
1.75	0.514	0.380	0.305	0.212	0.062	0.016	0.002					
1.50	0.481	0.343	0.285	0.173	0.041	0.011	0.000					

Table 8 (Cont.)

LEGENDRE EXPANSION COEFFICIENTS FOR U²³⁸

2.4.10 n, 3n Cross Section

The n, 3n cross section shown in Table 6 was also taken directly from Reference 5.

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Argonne National Laboratory (1)
P.O. Box 299
Lemont, Illinois
Attn: J. F. Marchaterre
Project Manager, ANL
Nuclear Rocket Study

Brookhaven National Laboratory (1)
Upton, Long Island, New York
Attn: Dr. J. L. Stehn